



Assessment of Trace and Heavy Metal Contamination in Soil: Distribution Patterns, Pollution Indices, and Environmental Risk Evaluation

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Abstract

Soil contamination by trace and heavy metals is an important environmental concern because of their persistence, accumulation, and potential ecological effects. This study assessed the concentration patterns and contamination status of trace and heavy metals using a publicly available Heavy Metal Study dataset obtained from Mendeley Data, comprising 44 soil samples collected from a granitic terrain in South India. The dataset included concentrations of 14 elements: As, Ba, Co, Cr, Cu, Mo, Ni, Pb, Rb, Sr, V, Y, Zn, and Zr. Descriptive statistics, Contamination Factor (CF), Geo-accumulation Index (Igeo), Pollution Load Index (PLI), and Pearson correlation analysis were applied. Considerable variability was observed among the elements, with Cr, Zr, Co, Zn, and Y showing the highest coefficients of variation. Zr recorded the highest mean CF and was classified as having very high contamination, while Pb, Mo, Y, and Ba showed moderate contamination. Most other elements generally exhibited low contamination levels. The Igeo results indicated predominantly uncontaminated to moderately contaminated conditions, although localized enrichment was observed in selected samples. Sample S3 emerged as the principal contamination hotspot and was the only sample with a PLI above 1. Strong positive correlations were observed among Co, Cr, Cu, and Ni, while Y and Zr showed an exceptionally strong association. Overall, the findings indicate limited regional contamination with distinct localized anomalies requiring continued environmental monitoring.

Keywords:

- Heavy metals
- Soil contamination
- Geo-accumulation index
- Pollution load index
- Environmental assessments

1. Introduction

The soil is a critical element of terrestrial ecosystem and is necessary for proper nutrient cycling, agricultural productivity, water regulation, carbon storage, and biodiversity conservation. Unfortunately, with the ongoing increase in industrial activity, urban sprawl, intensive farming practices, waste management, transportation, mining, and other human activities, there has been a gradual build-up of toxic substances in the soil (Tong et al., 2020; Din et al., 2023). In contrast to organic compounds, heavy metals are persistent, non-biodegradable, and can persist in the soil environment for quite long. The build-up of such compounds can affect soil characteristics, its microflora, plant productivity, and can be accumulated by plants and transferred further into the food chain (Huang et al., 2018; Gui et al., 2023). Hence, the assessment of soil metal contamination has become a significant part of environmental control measures and soil management practices (Ogwu et al., 2025).

The sources of trace and heavy metals in soils include both geogenic and anthropogenic factors. Geogenic inputs include weathering of parent materials, leaching, volcanic materials, and other pedogenic inputs, while anthropogenic inputs include emission from industries, metal processing, fertilizers, pesticides, sewage sludge, traffic, wastewaters irrigation, and improper dumping of wastes. The degree to which these sources play a role is greatly variable in different environments. A survey of soil contamination in Pakistan revealed that there was significant spatial variation in the metal(loid) contents and that geological features as well as anthropogenic factors were involved in environmental and ecological risks (Din et al., 2023). Such observations imply that an evaluation of the element distribution needs to be done considering the geological and environmental setting of the study region.

Environmental significance of metal contamination in soils is based not only on their concentrations but also on their enrichment in relation to the background concentrations. Toxic element accumulation may pose an ecological danger through alteration of biological processes in soils and even accumulation in plants and other living creatures. Soils close to the industry and smelting areas are especially prone to accumulation of various metals. Gui et al. (2023) revealed that soils located near the smelting zone were characterized by unique contamination distribution and had different levels of ecological and health dangers, which proves the necessity to identify not only contamination level but also distribution of dangerous elements.

A variety of pollution indices have thus been proposed to provide standardized measures of soil pollution. The Contamination Factor (CF) focuses on enrichments as compared with background levels of the pollutants, while the Geo-accumulation Index (Igeo) takes into account both pollutant concentration and natural variation associated with the geological setting. The Pollution Load Index (PLI) offers a composite index of total contamination with respect to several metals. The application of all three indices together enables more complete interpretation than just using concentration data. Spatial and statistical analysis techniques are also useful for pinpointing areas with higher concentrations and for determining the correlations between different elements. It was found in the geostatistical analysis of soil quality that heavy metals may have very heterogeneous spatial distribution even within one geographical area (Santos-Francés et al., 2017).

Metal accumulation and its environmental effects are especially pertinent when talking about urbanized environments. Indeed, a study on urban soils in China revealed that contamination rates differed significantly depending on the specific metal, location, and land use context and could be a cause of varying environmental concerns (Tong et al., 2020). Thus, analyzing patterns of contamination and singling out hotspots can help develop more effective soil management programs. More recent studies have proven the effectiveness of pollution index calculations combined with sophisticated classifications for detecting ecological risk patterns (Xiang et al., 2022).

The current study assesses the concentration and distribution of trace and heavy metals in 44 soil samples. In particular, the objectives of the study include characterization of the concentration and variability of the elements,

contamination assessment based on CF, Igeo, and PLI, and analysis of the relationship between elements to investigate any patterns that may exist. Through the use of both descriptive statistics and pollution index methods, along with correlation analysis, the study provides an overall analysis of soil pollution.

Objectives of the Study

- 1.To determine the concentration and distribution patterns of trace and heavy metals in the investigated soil samples.
- 2.To assess the level of soil contamination using the Contamination Factor (CF), Geo-accumulation Index (Igeo), and Pollution Load Index (PLI).
- 3.To evaluate inter-element relationships using Pearson correlation analysis and assess overall environmental contamination patterns.

2. Materials and Methods

2.1 Study Design and Data Source

A quantitative environmental assessment methodology has been adopted in this study, where the publicly accessible dataset for the Heavy Metal Study is used. The dataset, which is retrieved from Mendeley Data (More & Dhakate, 2025), consists of 44 soil samples (S1-S44) taken from a granite formation in South India. Concentration of 14 trace and heavy elements such as As, Ba, Co, Cr, Cu, Mo, Ni, Pb, Rb, Sr, V, Y, Zn, and Zr, measured in mg/kg, is provided.

2.2 Data Cleaning and Descriptive Statistics

Missing values, inconsistencies, and outliers were considered in the data preparation stage prior to the data analysis. Descriptive statistics, such as mean, median, standard deviation, minimum value, maximum value, and coefficient of variation (CV%), have been calculated for each element separately.

2.3 Pollution Indices

Contamination of soils has been evaluated using the following indices: Contamination Factor (CF), Geo-accumulation Index (Igeo), and Pollution Load Index (PLI). The calculation of CF includes the ratio of the measured elemental concentration to the background concentration.

The Geo-accumulation Index was calculated as:

$$I_{geo} = \log_2 [C_n / (1.5 \times B_n)]$$

where C_n represents the measured concentration of the element and B_n represents its background concentration.

The Pollution Load Index was calculated to assess the overall contamination status of each soil sample based on the combined contamination factors of the selected metals.

2.4 Environmental Contamination Evaluation

The contaminated state of the soils regarding their environment was determined according to the CF, Igeo, and PLI criteria. They were applied to determine elements that had high enrichment and soils as pollution spots.

2.5 Statistical Analysis

Pearson correlation analysis was conducted in order to reveal possible correlations between 14 analyzed elements and their distribution pattern. The statistical significance level was set at $p < 0.05$. The results were provided in tables and figures of pollution indexes and Pearson correlation heat map.

3. Results

Soil samples, totaling 44 in number, were studied for 14 trace and heavy metals, which include As, Ba, Co, Cr, Cu, Mo, Ni, Pb, Rb, Sr, V, Y, Zn, and Zr. There were no any missing values in the analyzed data set.

3.1 Distribution of Trace and Heavy Metals

Descriptive attributes of the studied elements are given in Table 1. Significant differences were found in element levels as well as sample variability.

Table 1. Descriptive statistics of trace and heavy metals in soil samples

Element	Mean $\pm$ SD (mg/kg)	Median	Minimum	Maximum	CV (%)
As	8.64 $\pm$ 3.18	8.25	3.4	19.6	36.78
Ba	789.89 $\pm$ 251.36	741.90	370.2	1710.6	31.82
Co	11.27 $\pm$ 13.54	8.85	0.3	89.6	120.17
Cr	51.66 $\pm$ 77.81	41.40	8.7	543.4	150.61
Cu	20.22 $\pm$ 13.53	18.25	7.7	96.6	66.89

Mo	4.31 ± 2.38	4.0 5	0. 2	12. 4	55.3 1
Ni	27.57 ± 24.59	24. 35	5. 4	16 8.0	89.1 9
Pb	41.39 ± 10.58	40. 60	4. 0	66. 0	25.5 6
Rb	131.80 ± 35.22	12 5.8 0	29 .6	22 3.0	26.7 2
Sr	243.91 ± 67.08	23 7.5 5	13 4. 6	43 7.9	27.5 0
V	80.87 ± 25.20	78. 40	39 .8	16 2.8	31.1 6
Y	40.18 ± 38.79	28. 85	10 .9	26 8.3	96.5 5
Zn	67.34 ± 67.83	54. 25	29 .1	47 8.3	100. 72
Zr	966.36 ± 1293.19	60 8.8 5	14 1. 2	82 32. 3	133. 82

Cr had the highest coefficient of variation (CV=150.61%), then followed by Zr (133.82%), Co (120.17%), Zn (100.72%) and Y (96.55%). Conversely, Pb, Rb and Sr had relatively lower CVs. Significantly high maximum concentrations were recorded for Cr, Zn, Y and Zr, implying localized elemental anomalies in the soils.

3.2 Contamination factor

Table 2 provides the mean values of contamination factor for the studied elements. The values indicate marked variations in enrichment compared to the set background values.

Table 2. Mean contamination factor and contamination classification

Element	Mean CF	Classification
Zr	6.040	Very high contamination
Pb	2.070	Moderate contamination
Mo	1.656	Moderate contamination
Y	1.545	Moderate contamination
Ba	1.362	Moderate contamination
Rb	0.941	Low contamination
Sr	0.813	Low contamination
Zn	0.709	Low contamination
As	0.665	Low contamination
V	0.622	Low contamination
Co	0.593	Low contamination
Cr	0.574	Low contamination
Cu	0.449	Low contamination
Ni	0.405	Low contamination

The element Zr had the highest mean CF (6.040) and was considered to be highly contaminated. Pb, Mo, Y, and Ba were moderately contaminated, while other elements were mostly lowly contaminated. In terms of individual samples, sample S3 exhibited high contamination factors for Cr (6.038), Co (4.716), Cu (2.147), and Ni (2.471). The element Zn was also highly contaminated with a CF value of 5.035 in sample S27. The trend of mean CF values is shown in Fig. 1, where reference lines with CF values of 1, 3, and 6 are used to separate contamination categories.

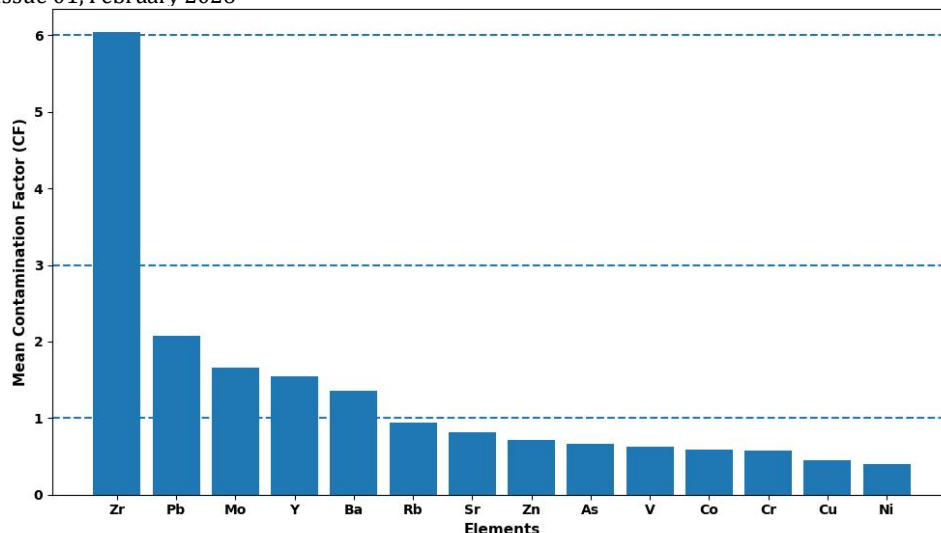


Figure 1. Mean contamination factor of trace and heavy metals in soil samples

Figure 1 clearly shows that zirconium (Zr) is the only metal element with a mean CF above the threshold value of 6. Lead (Pb), molybdenum (Mo), yttrium (Y) and barium (Ba) maintained the values of contamination between moderate, whereas all other elements were below the CF threshold value of 1. Hence, contamination in general occurred in a limited number of metals.

3.3 Geo-accumulation Index

For the most part, the results from the geo-accumulation index were mostly uncontaminated to moderately contaminated. However, some of the samples demonstrated high levels of contamination. In the sample S3, chromium (Cr) had the value of 2.009 of the Igeo, which corresponds to the classification of the moderately to heavily contaminated level, while cobalt (Co) is moderately contaminated, which is represented by the Igeo of 1.653. The element Zr recorded the highest enrichment factor across various soil samples. S1 and S4 were moderately to highly contaminated with Zr whereas S2 was highly contaminated. The highest Igeo value of Zr was obtained in S32 with 5.100, which indicates extreme enrichment. This clearly shows that though most soil samples contained relatively lower amounts of conventional heavy metals, some of them were highly enriched with Cr, Co, and Zr.

3.4 Pollution Load Index

The overall pollution status of the soil samples based on the Pollution Load Index is summarized in Table 3.

Table 3. Summary of Pollution Load Index across soil samples

PLI parameter	Result
Mean PLI	0.652
Median PLI	0.654
Minimum PLI	0.291
Maximum PLI	1.468
Samples with PLI < 1	43
Samples with PLI > 1	1

The average PLI value was 0.652, which ranged from 0.291 to 1.468. Out of the total 44 samples tested, only one sample (sample S3) had a PLI value greater than 1, showing presence of pollution; while 43 samples had PLI values less than 1, showing absence of any form of pollution. Therefore, there was low pollution load present in the samples analyzed, with sample S3 being the main hotspot.

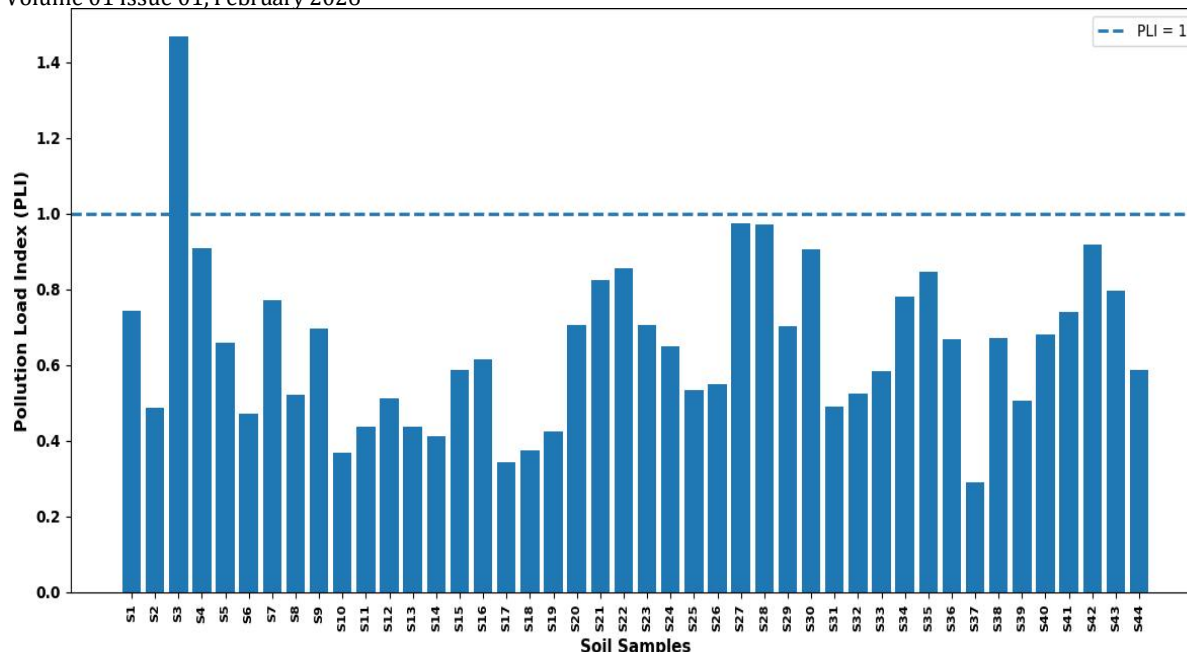


Figure 2. Pollution Load Index across the 44 investigated soil samples

As is evident from Figure 2, S3 alone was found to be above the pollution level of $PLI = 1$. There were several other samples close to the pollution line like S27 (0.975), S28 (0.971), S42 (0.916), S4 (0.908) and S30 (0.906).

3.5 Correlation Between Trace & Heavy Metals

Correlation analysis of Pearson method revealed various relationships between the studied elements. Some of the significant correlations are presented in Table 4 below.

Table 4. Major significant Pearson correlations among trace and heavy metals

Element Pair	Pearson r	p-value	Relationship
Y–Zr	0.983	<0.001	Very strong positive
Cu–Ni	0.967	<0.001	Very strong positive
Cr–Ni	0.949	<0.001	Very strong positive
Co–Cu	0.938	<0.001	Very strong positive
Cr–Cu	0.922	<0.001	Very strong positive
Co–Cr	0.916	<0.001	Very strong positive
Co–Ni	0.912	<0.001	Very strong positive
Co–V	0.599	<0.001	Moderate positive
Cu–V	0.569	<0.001	Moderate positive
Ba–Sr	0.564	<0.001	Moderate positive
As–Ba	0.549	<0.001	Moderate positive
As–Pb	0.531	<0.001	Moderate positive
Cu–Rb	–0.564	<0.001	Moderate negative
Ni–Rb	–0.562	<0.001	Moderate negative
Cr–Pb	–0.526	<0.001	Moderate negative

The highest positive correlation was found between Y and Zr ($r = 0.983$). There was another cluster with Co, Cr, Cu, and Ni elements that had a very strong positive correlation, with correlation coefficients varying between 0.912 and 0.967. Positive medium-level correlations were found between Co and V, Cu and V, Ba and Sr, As and Ba, and As and Pb. Negative medium-level correlations were seen in Cu and Rb, Ni and Rb, and Cr and Pb.

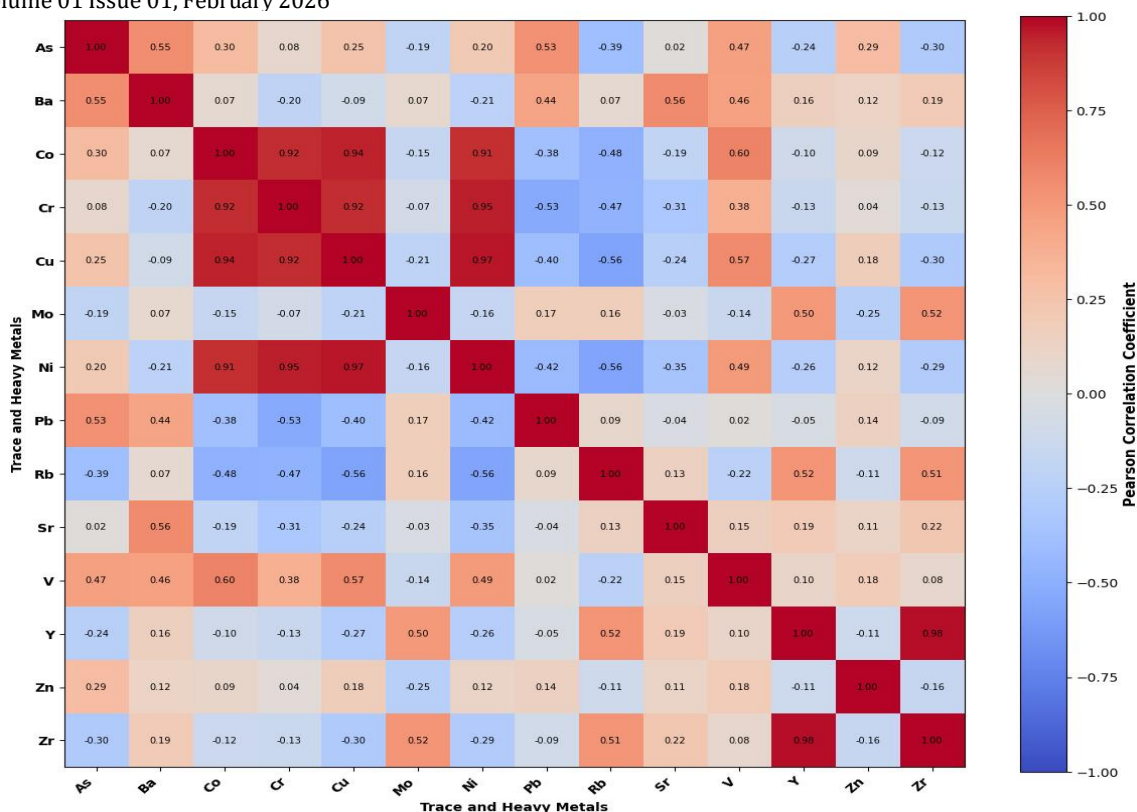


Figure 3. Pearson correlation matrix of trace and heavy metals in soil samples

Figure 3 shows the clustering of Co, Cr, Cu, and Ni elements, suggesting the same distribution pattern in all soil samples. The highly significant association between Y and Zr is clearly observable. On the other hand, negative correlations between Rb and Cu/Ni reveal the contrast in the behaviour of these elements. In general, the correlation pattern reveals that different elemental groups may have their separate geochemical or pollution processes.

Overall, most of the soil samples contained a trace and heavy metal contamination level ranging from low to moderate levels, except for certain localized anomalies. The highest element enrichment occurred in Zr, whereas Pb, Mo, Y, and Ba were moderately contaminated. The PLI results revealed that S3 was the only polluted sample due to its high concentration of Cr, Co, Cu, and Ni elements. Strong inter-elemental correlations such as Co, Cr, Cu, and Ni as well as Y and Zr further prove the associations among elemental groups.

4. Discussion

This study revealed the presence of mainly low to moderate levels of trace and heavy metal contamination in the analyzed soils, with significant differences between individual elements and samples. The highest degree of heterogeneity was found for Cr, Zr, Co, Zn, and Y, implying non-uniform distribution of these elements in the 44 studied soils. High values of the coefficient of variation point to the existence of local enrichment, which is likely due to the complex effect of geological and anthropogenic factors. Such findings agree well with the literature data showing high variation of heavy metals in soils due to differences in their geological origin, soil use, agricultural and industrial activity, and atmospheric deposition (Adimalla et al., 2019; Chen et al., 2021). Analogous pattern of spatial heterogeneity has also been identified in agricultural and peri-urban soils with localized accumulation of metals (Huang et al., 2018; Marrugo-Negrete et al., 2017).

The results of contamination factor analyses revealed that Zr possessed the highest mean value of CF, whereas Pb, Mo, Y, and Ba displayed moderate contamination. On the other hand, As, Co, Cr, Cu, Ni, Zn, and many other elements continued to belong to the low contamination group. Such results suggest that the overall contamination load was related only to a few elements. Similar applications of CF and other pollution indices have proven their effectiveness in distinguishing low background metals from enriched ones (Askari et al., 2020; Taghavi et al., 2024). Nonetheless, Zr with its high CF values must be considered cautiously since the investigated area has granitic rocks and Zr is known for its presence in resistant accessory minerals. Such facts suggest that the high CF values for Zr can be explained by lithogenic enrichment and not by direct anthropogenic contamination. It is especially important in view of the fact that recent works on the granitic regions have stressed the necessity of such differentiation (Hridoy et al., 2025).

The findings from geo-accumulation analysis also reinforced the low levels of pollution in most samples but highlighted some local anomalies. The sample S3 was particularly special as it recorded relatively higher concentrations of Cr, Co, Cu, and Ni, with Cr being in the moderately to highly contaminated state. The sample S27 also contained relatively high amounts of Zn, whereas the sample S32 had relatively high amounts of Zr. This shows that assessments of pollution based on average concentrations can actually overlook localized pollution. Previous research findings have suggested that in cases where the pollution index is used to analyze pollution, there is an isolated risk zone that can be considered at high risk of pollution despite relatively low contamination (Keshavarzi &

Kumar, 2020; Oghenenyoreme Eyankware et al., 2024). Pollution-index approaches are therefore valuable because they provide a clearer indication of contamination intensity than concentration data alone (Neeraj et al., 2023).

The Pollution Load Index gave an integration of the level of contamination and revealed that out of the total 44 samples collected, 43 had a PLI value less than one, hence there was no pollution. One of the samples that had PLI value above one is S3 and therefore, S3 becomes the main area of contamination. This result corroborates with the findings of previous researches that indicated that despite the area being relatively less polluted in terms of pollution, the PLI is able to detect the areas of pollution (Khan et al., 2022; Xiang et al., 2020). In the management of the environment, identifying the hotspot areas becomes very important.

In the case of the geochemistry and the potential of contamination in relation to the environmental management, Pearson correlation gives additional information on the geochemical behavior and the possible source of contamination. Very strong positive correlations of Co, Cr, Cu, and Ni indicates the same geochemical behavior or the same sources of these elements. Y-Zr strong correlation probably shows common source in form of the granitic parent material. The same application of inter-element correlation in distinguishing geogenic and anthropogenic origin of contaminants is evident in earlier studies dealing with polluted soils (Zhang et al., 2018; Ogwu et al., 2025). Inter-element correlations may also reveal common behavior of the elements in the environment, especially if there is a positive relationship between As-Pb and Ba-Sr, and a negative one between Rb and Cu, Ni.

There are many limitations in the study. The database comprised of just 44 samples and there was no data on land use, presence of industries, agricultural activities, physicochemical characteristics of the soils, and seasonality. In addition, the evaluation of pollution was based only on total element concentration and did not consider metal speciation and bioavailability. In other words, no direct biological effects were assessed. It is also known that pollution indices are highly dependent on the background values chosen. Further research should take into account a much bigger sample size, specific background concentrations, soil pH, organic matter content, soil texture, metal fractionation, and geographic coordinates. In addition, seasonal assessment and risk analysis will be of great help.

5. Conclusion

The current study represents an integrative approach to assessing contamination by trace and heavy metals in 44 soil samples using descriptive statistics, contamination indices, and correlation analysis. On the whole, the soils had rather low to moderate contamination, but element-specific and sample-specific outliers have been established. Cr, Zr, Co, Zn, and Y were the elements displaying the highest variance, which demonstrates high heterogeneity of their distribution. When considering the contamination level of the analyzed elements, Zr demonstrated the maximum mean contamination factor, while Pb, Mo, Y, and Ba had rather moderate levels of contamination. At the same time, As, Co, Cr, Cu, Ni, Zn, and many others had low contamination levels on the whole. Geo-accumulation analysis indicated rather low to moderate contamination of the majority of samples with local enrichment; S3 sample proved to be the main source of contamination by having rather high Cr, Co, Cu, and Ni content with the only Pollution Load Index greater than 1. The presence of highly significant positive correlation between Co, Cr, Cu, and Ni was an indication of similar behavior of the elements or possible same influence of sources whereas the presence of highly significant Y-Zr correlation suggested the probable existence of lithogenic affinity. The results obtained from the present study showed that there is no contamination at the regional level, although localized pockets of contamination do exist.

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